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14. ABSTRACT

Measurements of the heat transfer enhancement effects of concave spherical dimples have been performed under hydrogen-oxygen hot-fire conditions in a subscale combustion chamber. Seven configurations were tested with a range of area densities from 15-70% and depth to diameter ratios of 0.111 to 0.333. (Additional quantitiative results will included in the form of heat transfer coefficients and Stanton number.) Enhancements of 15-82% relative to a smooth surface were measured. Reynolds number was varied by a factor of 5 and was found to have an insignificant effect on the enhancement factor. Results correlated well with previous studies conducted under cold-flow conditions with similar values of area fraction, depth to diameter ratio and channel height to dimple diameter. These results are suitable for use by analysts and designers considering the use of heat transfer enhancement features on hot gas walls for example in the design of high performing expander cycles. Concave spherical dimples may have advantages over other approaches for enhancing heat transfer such as protruding ribs with respect to the integrity of the chamber wall and the efficiency of the heat transfer enhancement relative to the associated increase in skin friction.

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Measurements of the Effectiveness of Concave Spherical Dimples for Enhancement of Hot-gas Side Heat Transfer
(Preprint)

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Measurements of the heat transfer enhancement effects of concave spherical dimples have been performed under hydrogen-oxygen hot-fire conditions in a subscale combustion chamber. Seven configurations were tested with a range of area densities from 15-70% and depth to diameter ratios of 0.111 to 0.333. (Additional quantitiative results will included in the form of heat transfer coefficients and Stanton number.) Enhancements of 15-82% relative to a smooth surface were measured. Reynolds number was varied by a factor of 5 and was found to have an insignificant effect on the enhancement factor. Results correlated well with previous studies conducted under cold-flow conditions with similar values of area fraction, depth to diameter ratio and channel height to dimple diameter. These results are suitable for use by analysts and designers considering the use of heat transfer enhancement features on hot gas walls for example in the design of high performing expander cycles. Concave spherical dimples may have advantages over other approaches for enhancing heat transfer such as protruding ribs with respect to the integrity of the chamber wall and the efficiency of the heat transfer enhancement relative to the associated increase in skin friction.

Nomenclature

d	=	Dimple diameter
h	=	Dimple depth
H	=	Channel height
f	=	Fraction of surface covered by dimples
t	=	Dimple spacing
Nu	=	Nusselt number
P_c	=	Chamber pressure

I. Introduction

In an expander cycle rocket engine, the turbo-pump is driven by a gaseous propellant that has been heated in channels incorporated into the thrust chamber wall. The power output of the turbine is limited by the hot gas wall heat transfer coefficient and surface area. To increase the chamber pressure, additional pump power and heat are required. Part of the increase can come from an increased heat transfer coefficient at elevated chamber pressure but this is not sufficient and engine designs have also required an increase in surface area, typically by elongating the chamber, or a supplemental increase in heat transfer coefficient by one of the methods of heat transfer enhancement. In the Orbital Transfer Vehicle[1] program several styles of longitudinal ribs were examined and enhancements of 40-50% were measured. However, there are other approaches which should also be considered because the tips of ribs are vulnerable to hot spots and may become points of incipient failure.

In this study, we examined the effectiveness of concave spherical dimples (CSD). This method has been the subject of several previous investigations and has been found to have favorable characteristics with respect to the efficiency of heat transfer enhancement relative to the amount of skin friction created. CSD may also be less prone to the formation of hot spots and concentrations of mechanical stress. The main objective of this study was to

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develop a design space for heat transfer enhancement by characterizing the heat transfer effectiveness as a function of non-dimensional geometric parameters. This information should be of utility to thrust chamber design teams when performing trade studies involving heat transfer enhancement with other critical factors such as performance, weight and lifetime.

CSD patterns can be characterized with two non-dimensional numbers: the depth to diameter ratio, h/d, and the fraction of the surface covered by dimples, *f*. Other geometric parameters that may be significant in some applications are the channel height, H, and the arrangement of the rows of dimples, staggered or in-line. For reference, the maximum possible value of *f* is 0.91 and occurs when the edges of adjacent dimples are tangent. The maximum value of h/d occurs when the depth h is equal to the dimple radius, or h/d=0.5.
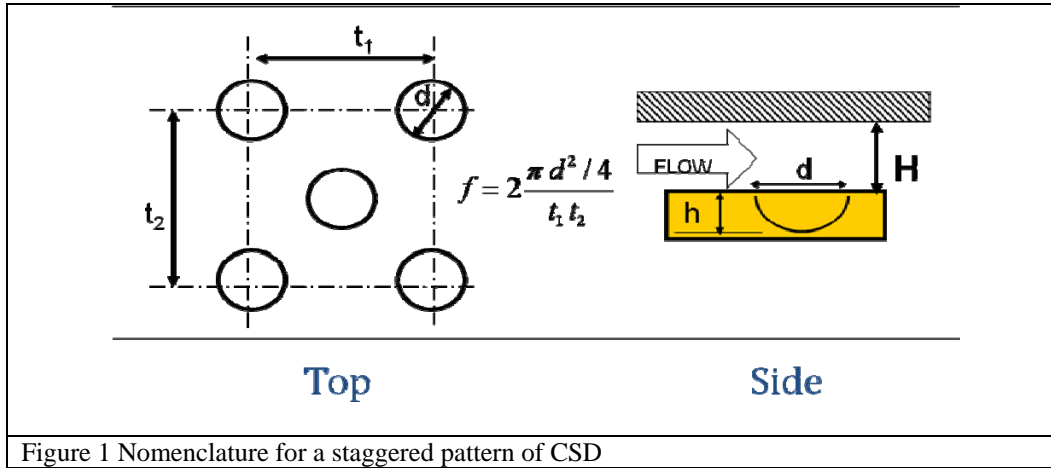

Figure 1 Nomenclature for a staggered pattern of CSD

Previous works on heat transfer enhancement using CSD are reviewed and summarized in Ligrani[2] (2003). The majority of previous efforts have been performed using nearly ambient air in flat channels with H/d in the range 0.2-2. Moon[3] (2000) examined the effect of channel height on Nusselt number for a staggered pattern of CSD with h/d=0.19 and *f*=0.57. The globally averaged heat transfer enhancement, Nu_{dimple}/Nu_{smooth} was approximately 2.1 and independent of channel height for a range of H/d of 0.35-1.5. Mahmood[4] (2002) described the flow patterns and measured local Nusselt number distributions over the surface for the same dimple pattern used by Moon. The most important features of the flow consisted of: (1) a shear layer that separates from the upstream edge and then reattaches on the downstream edge, (2) vortices that shed from the indentations and then advect over the flat surface downstream of the dimples, and (3) periodic unsteadiness as flow is ejected and then in-rushes. Local Nusselt numbers were in the range of 1-3.2 times that for a smooth plate. Burgess[5] (2003) examined the effect of varying h/d from 0.1-0.3 for a fixed value of *f*=0.57 and a fixed channel height, H/d=1. The enhancement increased with h/d and was correlated with the following equation:

$$\frac{Nu_{\dim ple}}{Nu_{smooth}} = 1 + 6.193\left(\frac{h}{d}\right)^{1.162} \tag{1}$$

Burgess also examined the effect of turbulence intensity in the channel and found that it had a weak effect on the enhancement factor.

There have been two studies that examined the case of dimples much smaller than the height of the channel. Afanaseyev[6] (1993) examined the case of a staggered pattern of shallow CSD with h/d=0.067 and *f*=0.25-0.70 in a channel with height of H/d=11-18. Heat transfer was increased by 30-40% with no measureable increase in friction factor. Bunker and Donnellan[7] (2003) examined six in-line patterns in a cylindrical tube with h/d=0.23-0.4, *f*=0.34-0.70, and H/d of approximately 4. Bunker reported that the enhancement was proportional to $f^{0.5}$ and reached a value of 2 for h/d>0.3 and f>0.5. The overall dependence of the Nusselt number was $Re^{.86}f^{0.5}$.

In summary, the studies to date have found that the major variables affecting heat transfer enhancement of CSD are h/d and *f* and Reynolds number effects are small. One study examined the effect of turbulence intensity and found it was weak. Based on these parameters, the data can be grouped into three categories and there is relatively little overlap between them. The works associated with Ligrani (Moon (2000), Mahmood (2002) and Burgess

(2003)) were all performed at *f*=0.57 and relatively small values of channel height, H/d=0.2-2. Small values for channel height result in flow disturbances from the dimples perturbing the flow across the entire channel. This condition is relevant to gas turbine blades but is not likely to be relevant to hot-gas wall heat transfer in liquid rocket engines. The studies of Afanaseyev and Bunker examined larger values of channel height and similar ranges of *f*, but different regimes of h/d, so it is not possible to make direct comparisons between the data sets. Furthermore, the correlations that have been proposed by Burgess and Bunker have not included data from the other studies and have been based on different and very limited ranges of f and h/d. Based on the literature review and in order to support the use of CSD in expander cycle combustion chambers, the following research needs were identified.

1. The ranges of *f* and h/d need to cover the entire design space.
2. Comparisons with previous studies must be performed to determine if the results are consistent.
3. The interactions between *f* and h/d need to be characterized. A complete response surface for heat transfer is needed.
4. A study should be performed under rocket chamber conditions because flow contained within the dimples will have properties significantly different from the freestream.
5. Large values of H/d should be examined.

Based on these considerations the experimental design given in Table I was formulated. All of the patterns used a staggered arrangement. The last column in the table is the increase in surface area due to the addition of CSD. A plot of the design points along with the points used in previous studies is given in figure 1. In addition to the dimpled surfaces, a smooth wall was also tested. The roughness height of the smooth surface was 19 microinches and was measured using a diamond-stylus profilometer.

Table 1 Dimensional data for CSD patterns used in this study

	d (in.)	h (in.)	h/d	*f* (%)	H/d	+Area
#1	0.212	0.024	0.111	15	4.7	1.007
#2	0.212	0.024	0.111	40	4.7	1.020
#3	0.212	0.024	0.111	70	4.7	1.035
#4	0.186	0.041	0.222	15	5.4	1.030
#5	0.186	0.041	0.222	40	5.4	1.079
#6	0.173	0.058	0.333	15	5.8	1.066
#7	0.173	0.058	0.333	70	5.8	1.309

Figure 2 CSD parameters used in this study and previous studies
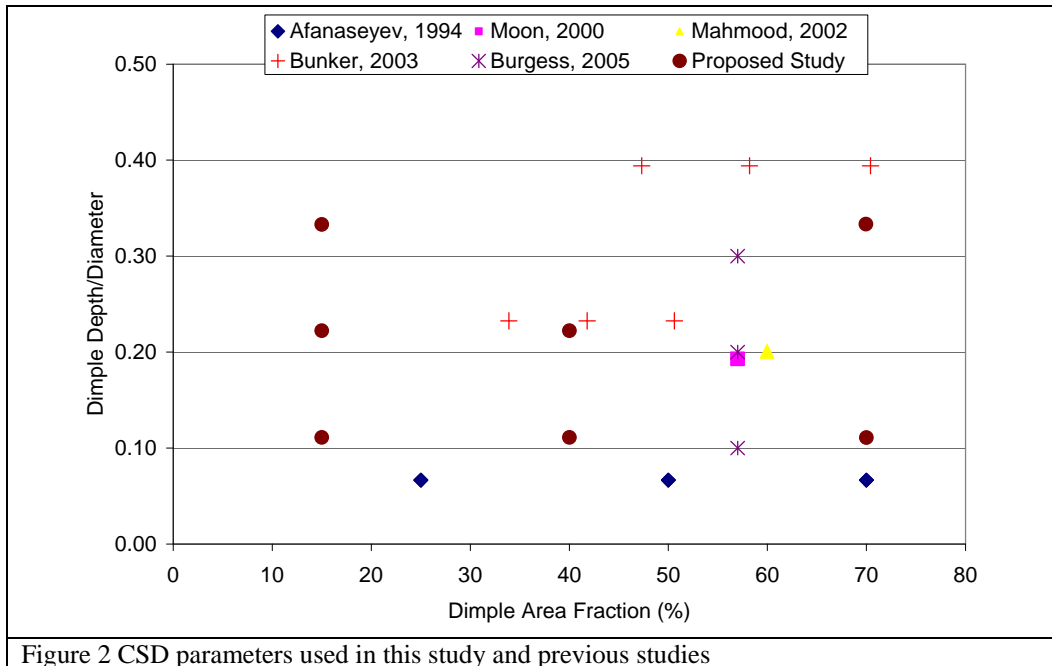
II. Results and Discussion

Tests were conducted in the AFRL, Aerophysics Branch Heat Transfer Rig which has been described previously in Coy (2007)[8]. For these tests the rig consisted of a gas-generator section with a 2"x2" cross-section, a contraction to a 1"x1" cross-section, a test article containing the test specimens, a square to round transition and then a nozzle with a throat diameter of 0.650". The injector consisted of 25 shear coaxial elements arranged in a 5x5 square array. The propellants were gaseous oxygen and gaseous hydrogen and all tests were conducted at a nominal oxygen to hydrogen mixture ratio of 5.5. Each specimen was tested over a range of chamber pressures from 100-500 psig in 100 psi increments. The test article is a heat-sink design with thick-walled sections of oxygen-free, high-conductivity copper. Run times ranged from 0.4 to 3 seconds. The rig reaches quasi-steady conditions in approximately 0.2 seconds.

Heat flux and surface temperature were measured using a technique based on measurements of temperature and rates of change of temperature using embedded thermocouples. A complete discussion of the theory is given in Coy[9] (2008). The implementation of the technique required designing in features which ensured the assumptions of the theory were valid. The thermocouples had to be installed in a way that did not perturb the flow of heat and the specimens were designed to ensure the flow of heat was one-dimensional. The test specimens were fabricated in two halves with the split along the axial centerline of the test articles. Grooves were milled into one of the mating surfaces to accept the thermocouple wires at a precise distance from the hot-gas surface (see figure 3). The halves were brazed together with Silvalloy15 in a hydrogen atmosphere furnace. Since the braze joint is on a plane of symmetry and is approximately .005" wide and is itself comprised of a relatively high thermal conductivity material, it has minimal effect on the flow of heat. To reduce the effects of axial conduction, gaps .010" wide were included in the heat flux blocks at 1" intervals. The effects of transverse conduction across the channel were minimized by the gaps and contact resistance between the test article and the specimens. In every test the first measurement station exhibited much faster temperature rise than the downstream locations. Therefore the data from the ends of the specimens were discarded and only the center 4 transducers were used to calculate the heat flux.

Measurements using a smooth block indicated that the entrance length effect in the test rig was approximately 6 inches. This entrance length corresponds well to that found previously by Bunker. The additional turbulence created by CSD is expected to further decrease the entrance length. However, to ensure the flow was fully developed by the center of the test specimens an additional 2 inch long section was added directly upstream of the test article to bring the number of channel heights at the measurement location to 6.5.

A chamber pressure trace from a typical firing is shown in figure 5, temperature traces from a test specimen are shown in the figure 6 and a calculated heat flux is shown in figure 7. The wall temperature is increasing over the duration of the test but the heat flux is fairly constant or slightly decreasing. For this test the data used to obtain the heat transfer enhancement factor was obtained by averaging heat flux over a data window from 1.8 to 2.1 seconds which falls within the interval of steady chamber pressure.

Figure 3 Installation of 0.063" thermocouples.

The heat flux to the wall depends on the heat transfer coefficient and the temperature difference between the wall and bulk fluid. The bulk fluid temperature is in the range of 5660^0 F so the percentage change in heat flux due to the change in wall temperature is quite small, approximately 5%, so the heat flux is quasi-steady. The total amount of heat transfer that occurred in the test article up to the throat can be estimated from a C* efficiency calculation. For all of the tests in this study C* efficiency was approximately 90%, therefore gas conditions were assumed to not depend on the CSD pattern.
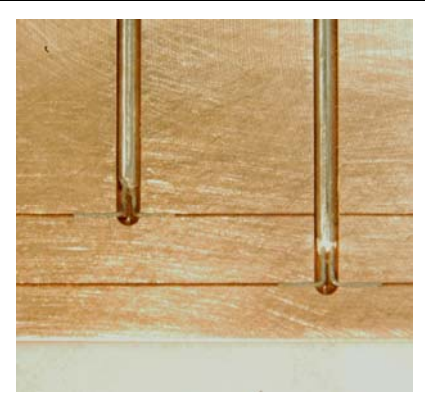
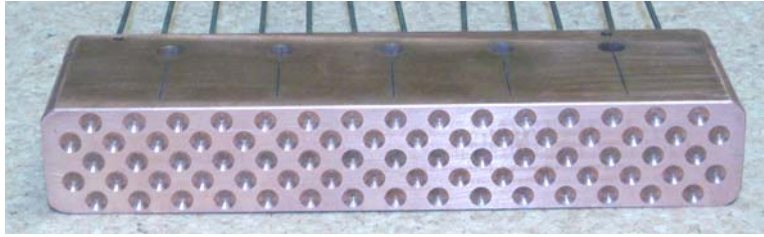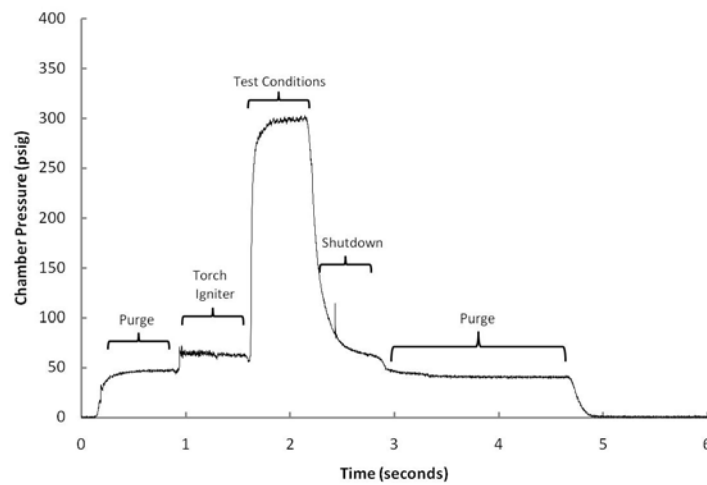Figure 4 Typical specimen prior to test

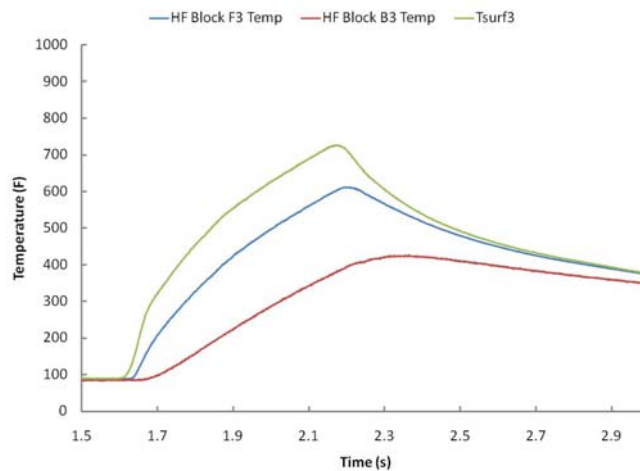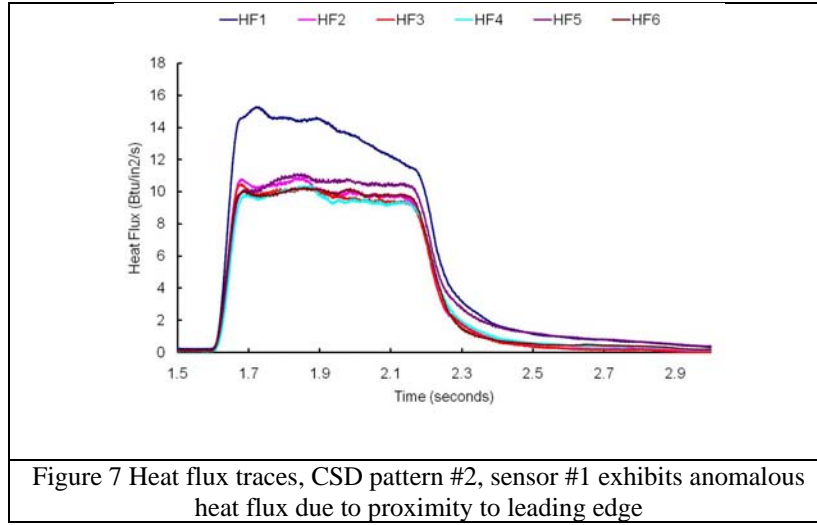Figure 5 Typical chamber pressure trace, CSD pattern #2, Run 134, Pc=300 psig

Figure 6 Temperature traces from embedded thermocouples and calculated surface temperature, CSD pattern #2, Run 134, sensor position 2.5 inches from leading edge.

Figure 7 Heat flux traces, CSD pattern #2, sensor #1 exhibits anomalous heat flux due to proximity to leading edge

The heat flux data for the CSD specimens as well as for the smooth wall were correlated with $Pc^{0.8}$. This relationship has been observed many times by others and has been codified in the well-known correlation of Bartz[10]. All of the data follows the expected correlation quite well except for the #7 specimen with f=0.7 and h/d=0.333. This case was fit more closely by $Pc^{0.7}$; however, for consistency with the other cases the results presented here also assumed $Pc^{0.8}$. Figure 8 contains a plot for several of the cases along with the regression lines. The R^2 statistics for the linear regression lines for all of the specimens fell between 0.992 and 0.999. The overall heat transfer enhancement factors were obtained from the ratio of the slopes of the regression lines for the CSD specimens with the smooth specimen. The fact that CSD specimens exhibited the same $Pc^{0.8}$ scaling as the smooth specimen confirmed the observation made in previous studies that the heat transfer enhancement effect is nearly independent of the Reynold's number. The results are given in Table 2 and comprise the major results of this study.

Table 2 Heat transfer enhancement factors. Current study.

Specimen	f (%)	h/d	Enhancement
Smooth	0	0	1.00
#1	15	0.111	1.15
#2	40	0.111	1.40
#3	70	0.111	1.48
#4	15	0.222	1.34
#5	40	0.222	1.54
#6	15	0.333	1.31
#7	70	0.333	1.82

Table 3 Bunker and Donnellan (2003)

f (%)	h/d	Enhancement
70.4	0.394	2.0
58.2	0.394	1.9
50.6	0.233	1.7
47.3	0.394	1.8
41.8	0.233	1.6
33.9	0.233	1.25

Table 4 Afanaseyev (1994)

f (%)	h/d	Enhancement
25	0.067	1.1
50	0.067	1.36
70	0.067	1.54

Figure 8 Scaling of heat transfer with $Pc^{.8}$
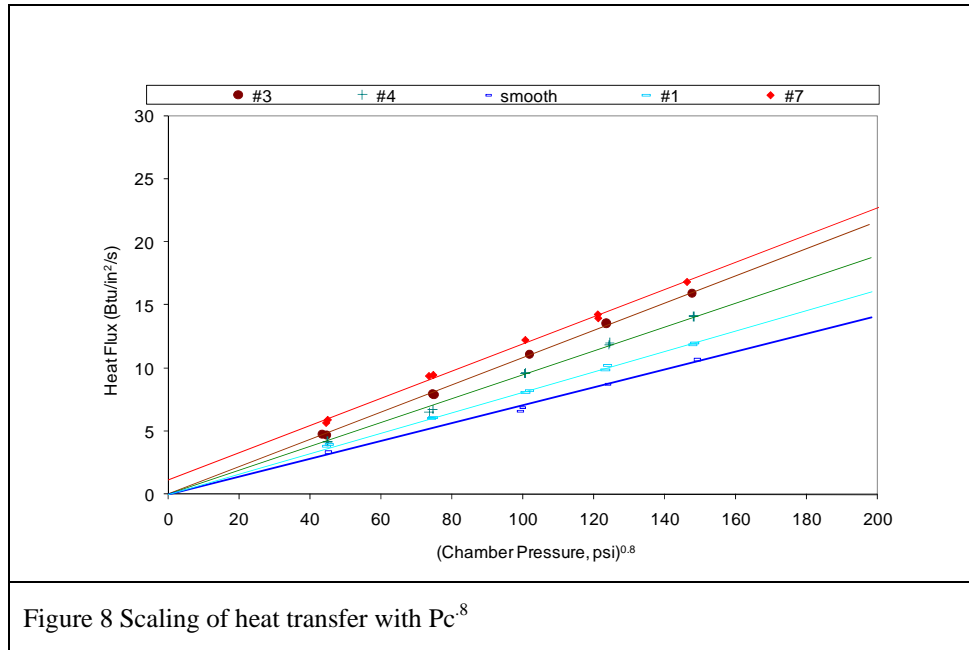
III. Results

Data from this study as well as the two previous studies with large H/d, Tables 3 and 4, are presented in figure 9. Contour levels have been fit using Delauney triangulation with a linear function. The surface passes through each data point and uses linear triangulation to interpolate between the points. The contours were obtained with the Matlab function *griddata* with the *'linear'* interpolation method. The agreement with the previous work of Bunker and Afanaseyev is excellent with one exception. That one is the point of Bunker with f=0.339 and h/d=0.233. This point also appears to not follow the trend of the other data in figure 9 of Bunker (2003). Although we can site no technical basis for excluding this point it does not appear to fit with the other data and therefore we have chosen to treat it as an outlier and have not included it in the figure. The fact that the data of this study agrees well with the results of the earlier, nearly-ambient studies, indicates that heat transfer enhancement is not significantly affected by strong property gradients.

We can make a few general observations about the disposition of the data in figure 9. The contours at low values of f are nearly vertical indicating that the enhancement factor is a function of f only and nearly independent of

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the h/d parameter, while at high values of f the contours are horizontal indicating that enhancement is a function of h/d only and independent of f. In the mid-range of the parameters there is a significant interaction f and h/d.

Bunker and Donnellan (2003) observed that there was relatively little effect of f above a value of 0.5 and this has been confirmed here. However, the observation that enhancement is proportional to $f^{0.5}$ has not been confirmed and may only be valid in the range of parameters used in their study.

The data from studies with small values of H/d are not included in the figure. The enhancement factors measured in those studies were in the range of 2-2.5, approximately 35% larger than those measured here. The specific trend with respect to h/d that was reported by Burgess (2003) and given above as equation (1) appears likely to be valid only for the particular value of f and H/d used in that study. The result of Moon (2000) that enhancement is independent of channel height is also not valid for the conditions of this study. Moon obtained the results for channels with 0.37<H/d<1.49 which may lie in a different regime than H/d>4.5 considered here.

A final observation is that the increase in heat transfer is significantly larger than the increase in surface area as can be seen by comparing Table 2 with the last column in Table 1.

Additional results will be included in the final version on heat transfer coefficient and Stanton number along with comparisons to standard correlations such as Bartz.
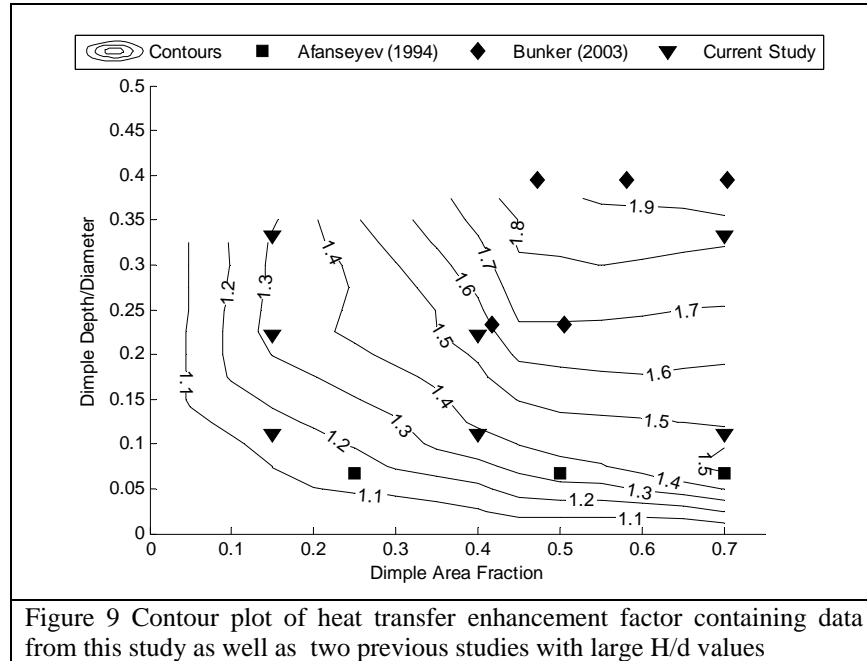

Figure 9 Contour plot of heat transfer enhancement factor containing data from this study as well as two previous studies with large H/d values

IV. Summary

This study measured the effectiveness of concave spherical dimples for enhancing heat transfer under conditions relevant to high-performing, expander-cycle, liquid rocket engines. Seven dimple patterns were tested and were compared to results for a smooth specimen. The dimensions of the patterns were chosen to span the range of possible values. Some conclusions obtained by other researchers under near-ambient conditions were confirmed. The enhancement increased with f for all values of h/d up to a value of approximately f=0.5 and then did not increase further, and the enhancement was independent of Reynolds number. However this study did not confirm previously reported measurements of the scaling of heat transfer enhancement with h/d and f. For values of f less than 0.2 the enhancement became independent of h/d for values of h/d>0.15, while for values of f>0.5, the enhancement continued to increase with h/d up to the highest values that have been tested (h/d=0.394). Also, previous studies treated h/d and f as independent variables while this study found a strong interaction between these variables. Finally, the results of this study agreed well with previous studies that examined the case of channel

heights much larger than the dimple diameter, H/d>4.5, but did not agree with a study that examined 0.37<H/d<1.49 and found no effect of H/d and this indicates that there can be an effect of H/d on heat transfer enhancement.

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